

Performance Analysis of Natural Fiber-Reinforced Composites: A Systematic Review of Materials, Fiber Architectures, Fabrication Routes, And Data-Driven Modelling

Prathama Lokhande¹, Rameshwar Khanpate², Dr. Sanjeevmurthy³

¹Student, Yadavrao Tasgaonkar Institute of Engineering and Technology (YTIET)

²Research Scholar, Shri Siddhartha Academy of Higher Education (SSAHE)

³Professor, Shri Siddhartha Institute of Technology (SSIT)

Abstract

Natural fiber-reinforced composites (NFRCs) are increasingly considered for lightweight automotive parts, building products, furniture, packaging, sporting goods, and additively manufactured components because plant-derived reinforcements can reduce density and synthetic-fiber consumption while retaining useful specific mechanical properties. This review critically analyses how composite performance is governed by the coupled selection of matrix material, fiber species and architecture, surface modification, reinforcement loading, and fabrication route. A PRISMA-guided structured search covering 2020–June 2026 was applied to peer-reviewed experimental, computational, and modelling studies indexed through major scholarly databases and publisher platforms. From 650 initially identified records, 28 studies satisfied the final eligibility and quality criteria. The evidence was classified into thermoset, thermoplastic, bio-based and hybrid matrices; short, aligned, woven and hybrid reinforcement forms; hand lay-up, compression moulding, vacuum-assisted processing, extrusion/injection moulding and fused deposition modelling; and finite-element, response-surface and machine-learning approaches. Reported results show that high alignment and adequate impregnation can produce substantial gains, such as 44.8 MPa tensile strength and 97.6 MPa flexural strength in 60 wt% aligned hemp/polypropylene composites, whereas poorly bonded kenaf/ABS printed composites showed strength loss at intermediate fiber loading. Sodium bicarbonate, alkali and plasma treatments can improve interfacial transfer, but their effects are fiber-specific and excessive treatment may damage cellulose. Hybridization improves property balance, and recent ensemble models have achieved R^2 values of 0.94–0.99 for flexural-strength prediction. The principal gaps are inconsistent specimen preparation, limited cross-process comparison, insufficient durability data, small and heterogeneous datasets, and weak integration of mechanical performance with cost and life-cycle indicators. The review concludes that NFRC design should be treated as a coupled material–interface–process optimization problem supported by standardized testing and interpretable computational tools.

Keywords— *natural fiber-reinforced composites; fiber–matrix interface; surface treatment; compression moulding; vacuum infusion; fused deposition modelling; machine learning.*

1. Introduction

This systematic review examines natural fiber-reinforced composites that combine lignocellulosic or animal-derived reinforcements with thermoset, thermoplastic, mineral, or bio-based matrices. Their attraction originates from low density, renewability, comparatively safe handling, and the possibility of using agricultural residues or rapidly renewable fibers in products traditionally made from glass-fiber composites. Recent industrial development has moved beyond simple particulate-filled plastics toward aligned mats, woven fabrics, hybrid natural–synthetic laminates, bio-polymer matrices, and additively manufactured feedstocks [1]. However, the term natural fiber composite covers material systems with markedly different chemical compositions and microstructures. Cellulose-rich jute, flax, hemp, kenaf and bamboo can provide high stiffness and strength, while lignin-rich coir tends to exhibit greater extensibility and impact-energy absorption. Matrix polarity, viscosity and curing behaviour determine whether these intrinsic fiber properties are transferred to the composite. Consequently, performance cannot be inferred from fiber name alone; it is an emergent result of the material combination, interfacial chemistry, architecture and processing history [2]–[6].

The current literature demonstrates both the promise and variability of NFRCs. Atmakuri et al. reported a flexural strength of 87.57 MPa for a 25 wt% hemp/15 wt% flax epoxy hybrid, whereas Sunny and Pickering obtained 44.8 MPa tensile strength, 6.2 GPa tensile modulus and 97.6 MPa flexural strength from highly aligned hemp/polypropylene containing approximately 60 wt% fiber [3], [7]. By contrast, Han et al. observed that kenaf addition to ABS filament

reduced tensile strength from 23.20 MPa for neat ABS to 11.48 MPa at 5% kenaf, before partial recovery to 18.59 MPa at 10%, because porosity, fiber pull-out and weak compatibility dominated the reinforcement effect [8]. These differences illustrate that volume fraction, architecture and impregnation quality can reverse expected material trends. Hybridization can improve property balance: flax–waste-glass laminates produced through autoclave consolidation showed flexural and impact improvements, and jute–glass stacking sequences produced high specific mechanical performance when glass plies were positioned to carry peak tensile and bending stresses [9], [10].

The fiber–matrix interface remains the major technical limitation. Natural fibers contain hydroxyl groups and absorb moisture, whereas most polymer matrices are hydrophobic. Weak wetting promotes interfacial gaps, swelling, matrix microcracking, and fiber pull-out. Alkali, silane, sodium bicarbonate and plasma treatments are therefore used to remove waxes and hemicellulose, increase roughness, change surface energy and improve mechanical interlocking. Nevertheless, treatment response is not universal. Fiore et al. found that sodium bicarbonate treatment substantially preserved the storage modulus of flax/epoxy during salt-fog ageing, yet the same treatment reduced initial jute-laminate stiffness [4]. Rachtanapun et al. increased bamboo/epoxy tensile strength from approximately 37 to 45 MPa using optimized argon-plasma exposure, but excessive energy or duration may etch or embrittle the fiber [11], [12]. Manufacturing adds a second source of uncertainty: hand lay-up is economical but operator-dependent, while compression moulding and vacuum-assisted resin transfer moulding generally improve thickness control and void removal. Extrusion and fused deposition modelling enable scalable or complex geometries, but short-fiber orientation, filament consistency and interlayer bonding become critical [13], [8].

A systematic synthesis is therefore necessary to connect constituent selection with fiber characteristics, processing quality, measured properties, durability, and predictive modelling. Existing papers frequently examine one material system or one fabrication route, employ different standards and conditioning regimes, and report incompatible metrics. The present review aims to establish an integrated performance framework for NFRCs. Its objectives are to: (i) compare matrix systems and natural-fiber types; (ii) evaluate the effects of fiber loading, length, orientation, architecture and treatment; (iii) analyse the strengths and limitations of hand lay-up, compression moulding, vacuum-assisted processing, thermoplastic compounding and additive manufacturing; (iv) assess finite-element, optimization and machine-learning methods; and (v) identify reproducibility, durability and industrialization gaps. The scope covers polymer-matrix and selected cementitious natural-fiber composites published mainly from 2020 to June 2026. Four research questions are addressed: Which material–fiber combinations provide the most useful performance balance? How does fabrication route control interface quality and defects? Which evaluation and predictive methods are reliable across heterogeneous studies? What standardization and future research are required for practical adoption? Section 2 describes the review protocol, Section 3 synthesizes related work through five themes, Section 4 provides critical discussion, Section 5 states review limitations, and Section 6 presents the conclusion.

2. Research Method

This review adopted a systematic literature review approach to evaluate the performance of natural fiber-reinforced composites based on matrix material, fiber characteristics, treatment methods, and fabrication processes. Relevant studies published mainly between 2020 and 2026 were identified through Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, IEEE Xplore, and Google Scholar. Search terms included “natural fiber composite,” “mechanical performance,” “fiber surface treatment,” “fabrication technique,” “hybrid composite,” and “thermal properties.” Peer-reviewed English-language journal and conference papers with full-text availability, clear experimental methodology, and reported technical results were included. Duplicate records, irrelevant studies, abstract-only publications, and non-scholarly sources were excluded. The studies were screened through identification, title and abstract review, full-text eligibility assessment, and final inclusion following a PRISMA-based process. Extracted information included fiber type, matrix, reinforcement content, orientation, fabrication method, mechanical, thermal, electrical, physical, and wear properties, major findings, limitations, and future research directions.

2.1 Review Design

The study adopted a structured systematic literature review supported by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework [1]. A hybrid design was used because the evidence base contains experimental material-characterization papers, fabrication studies, numerical investigations and machine-learning applications that cannot be combined through a conventional statistical meta-analysis. The protocol therefore integrated systematic identification and eligibility screening with thematic classification and quantitative extraction of directly reported material, process and performance values. The review unit was a peer-reviewed paper that

experimentally or computationally examined a natural-fiber composite and reported sufficient information on constituents, processing, evaluation and outcomes. A formal meta-analysis was not attempted because the studies differed in reinforcement fraction, matrix grade, specimen geometry, standards, loading rate and conditioning. Instead, numerical findings were normalized by unit, checked against the original tables or abstracts, and interpreted through within-study trends and physically comparable groups.

2.2 Data Sources

Searches were performed through Google Scholar and the publisher platforms ScienceDirect, SpringerLink, MDPI, Wiley Online Library, Taylor & Francis Online, SAGE Journals and IEEE Xplore. Scopus and Web of Science indexing status was checked when available to support source-quality screening. Crossref and publisher citation tools were used to confirm bibliographic metadata and digital object identifiers. The search focused on materials science, polymer science, mechanical engineering, manufacturing, civil engineering and sustainable materials. Full text was obtained from open-access publisher pages, institutional repositories or author-archived versions; abstract-only records were not used for quantitative comparison.

2.3 Search Strategy

The formal search covered 1 January 2020 to 30 June 2026; influential pre-2020 sources were retained only when needed to explain established terminology or testing practice. English-language journal articles and full conference papers were considered. The core Boolean strings were: (“natural fiber reinforced composite” OR “natural fibre reinforced polymer”) AND (mechanical OR thermal OR wear OR dielectric); (“jute” OR “flax” OR “hemp” OR “kenaf” OR “sisal” OR “bamboo” OR “coir” OR “banana”) AND (epoxy OR polyester OR polypropylene OR PLA OR ABS) AND (“hand lay-up” OR “compression moulding” OR VARTM OR extrusion OR “fused deposition modelling”); (“surface treatment” AND “natural fiber composite”) AND (alkali OR silane OR bicarbonate OR plasma); and (“natural fiber composite”) AND (“finite element” OR optimization OR “machine learning” OR “artificial neural network”). Database filters were applied for engineering and materials subject areas, peer-reviewed document type, English language and full-text availability. Backward and forward reference checking was used to identify additional studies. Search results were exported into a master screening sheet containing title, year, source, DOI, document type and retrieval status. Search strings were adapted only for database syntax; the conceptual terms and year restrictions were retained. The final search update was completed on 30 June 2026 so that early-view and 2026-indexed records could be considered without mixing incomplete future publication periods.

2.4 Inclusion Criteria

- Peer-reviewed journal articles or complete conference papers directly concerned with natural-fiber-reinforced composites.
- Full-text English publications containing an identifiable fiber, matrix and fabrication or modelling method.
- Studies reporting measurable technical results, such as tensile, flexural, impact, wear, thermal, water-absorption, dielectric or prediction metrics.
- Adequate description of specimen preparation, experimental conditions, numerical model or machine-learning workflow.
- Publication primarily within 2020–June 2026, with a limited number of foundational sources included for context.

2.5 Exclusion Criteria

- Duplicate records or papers using the same dataset without a distinct methodological contribution.
- Studies unrelated to natural-fiber reinforcement, or focused solely on synthetic fibers without a natural-fiber comparison.
- Abstract-only publications, unavailable full text, non-English papers, editorials, blogs, news items and non-scholarly webpages.
- Papers with incomplete constituent, fabrication or evaluation information that prevented technical interpretation.
- Review articles used only for background but not treated as primary evidence in the comparative performance tables.

2.6 Study Selection Process

The combined searches identified 612 database records and 38 additional records through reference-chain and manual publisher searching, giving 650 records. After removal of 146 duplicate entries, 504 titles and abstracts were screened.

A total of 389 records were excluded for lack of direct relevance, leaving 115 full-text papers for eligibility assessment. Eighty-seven full texts were excluded: 28 concerned an unrelated material or application, 21 lacked adequate technical results, 14 were not available as complete text, 11 were editorials or non-peer-reviewed sources, seven duplicated or substantially overlapped another dataset, and six were non-English. The final synthesis therefore included 28 primary studies. These values are used consistently in the PRISMA diagram and the subsequent classification.

2.7 PRISMA Flow Diagram

The PRISMA flow diagram presents the systematic process used to identify, screen, assess, and select studies for the review on natural fiber-reinforced composites. Initially, 612 records were retrieved from scholarly databases and publisher platforms, while 38 additional studies were identified through manual and citation searching, producing 650 records. After removing 146 duplicate records, 504 unique studies were screened using their titles and abstracts. During this stage, 389 records were excluded because they did not satisfy the preliminary relevance criteria. Consequently, 115 full-text articles were retained for detailed eligibility assessment. This structured screening procedure demonstrates that the review applied predefined selection criteria rather than relying on an arbitrary choice of publications.

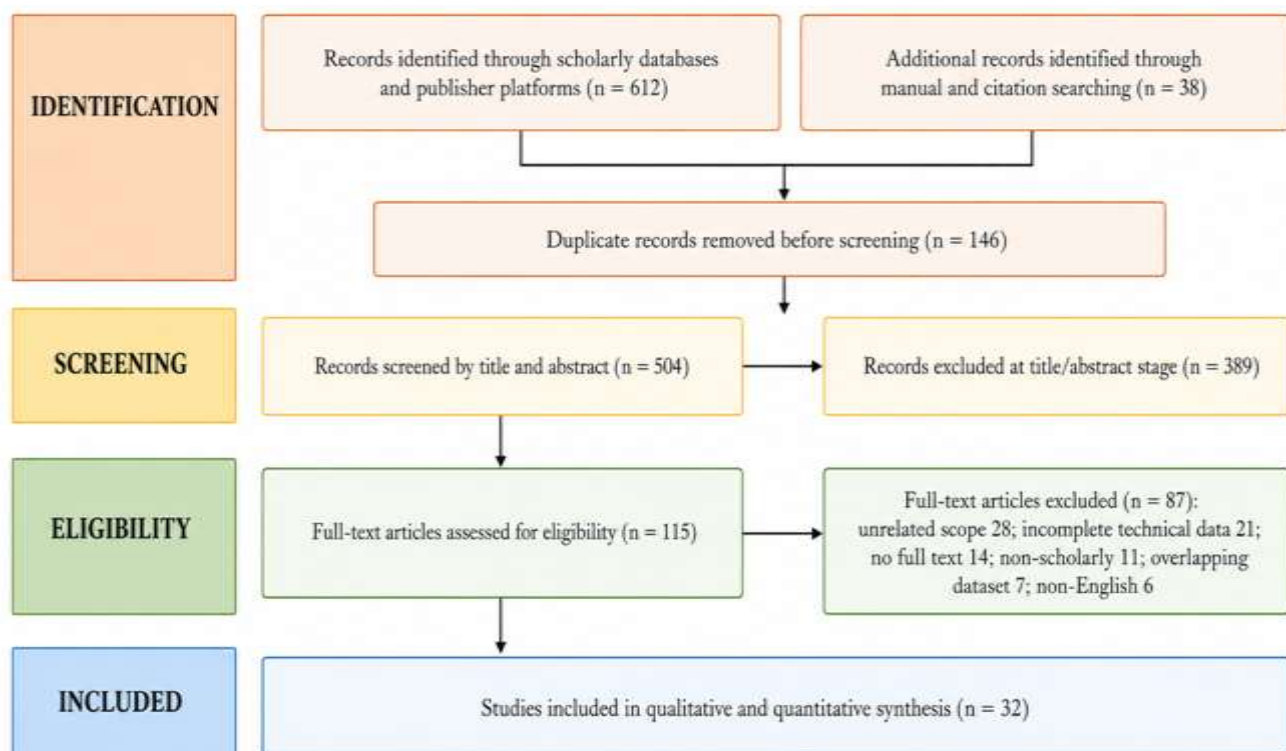


Fig. 1. PRISMA-based study identification and selection process.

During the eligibility stage, 87 full-text articles were excluded for specific reasons, including unrelated scope, incomplete technical data, unavailable full text, non-scholarly publication type, overlapping datasets, and non-English language. These reasons indicate that methodological quality, accessibility, relevance, and data completeness were considered before final inclusion. However, the numerical sequence requires correction because subtracting 87 excluded articles from 115 assessed articles gives 28 included studies, whereas the diagram reports 32. Therefore, either the number of full-text exclusions should be revised to 83 or the final included count should be changed to 28 to maintain internal consistency.

2.8 Data Extraction and Classification

A standardized extraction sheet recorded author and year, research objective, fiber species, fiber form, matrix, treatment, reinforcement fraction, fabrication method, specimen or dataset size, experimental standard, software or analytical model, evaluation indicators, principal numerical results, failure observations, limitations and proposed future work. Values were copied only when explicitly reported by the original paper; “not reported” was used where a metric was unavailable. Studies were segregated into five thematic groups: (i) matrix and constituent selection; (ii) fiber type, architecture and interface modification; (iii) fabrication routes and process-induced defects; (iv) numerical, optimization and machine-learning methods; and (v) comparative applications, durability and emerging gaps. Because test standards and material systems were heterogeneous, numerical values were interpreted as within-study evidence rather than a

universal ranking. Reported units were converted to MPa, GPa, kJ/m², wt% or vol% where the conversion was unambiguous. Reinforcement percentage was retained exactly as reported because weight and volume fractions are not interchangeable without constituent densities. When several formulations were tested, the best-performing formulation and the control were extracted together to preserve the direction and magnitude of the effect. Failure mechanisms were coded as fiber pull-out, fiber fracture, matrix cracking, interfacial debonding, delamination, porosity or agglomeration.

3. Related Work

The related work on natural fiber-reinforced composites demonstrates that composite performance is governed by the combined influence of the matrix system, reinforcement architecture, and manufacturing route. As illustrated in the taxonomy, thermosetting matrices such as epoxy, polyester, and vinyl ester are widely adopted for high-strength laminates, whereas thermoplastics including polypropylene, polyethylene, polylactic acid, and acrylonitrile butadiene styrene support recyclable and mass-production applications.

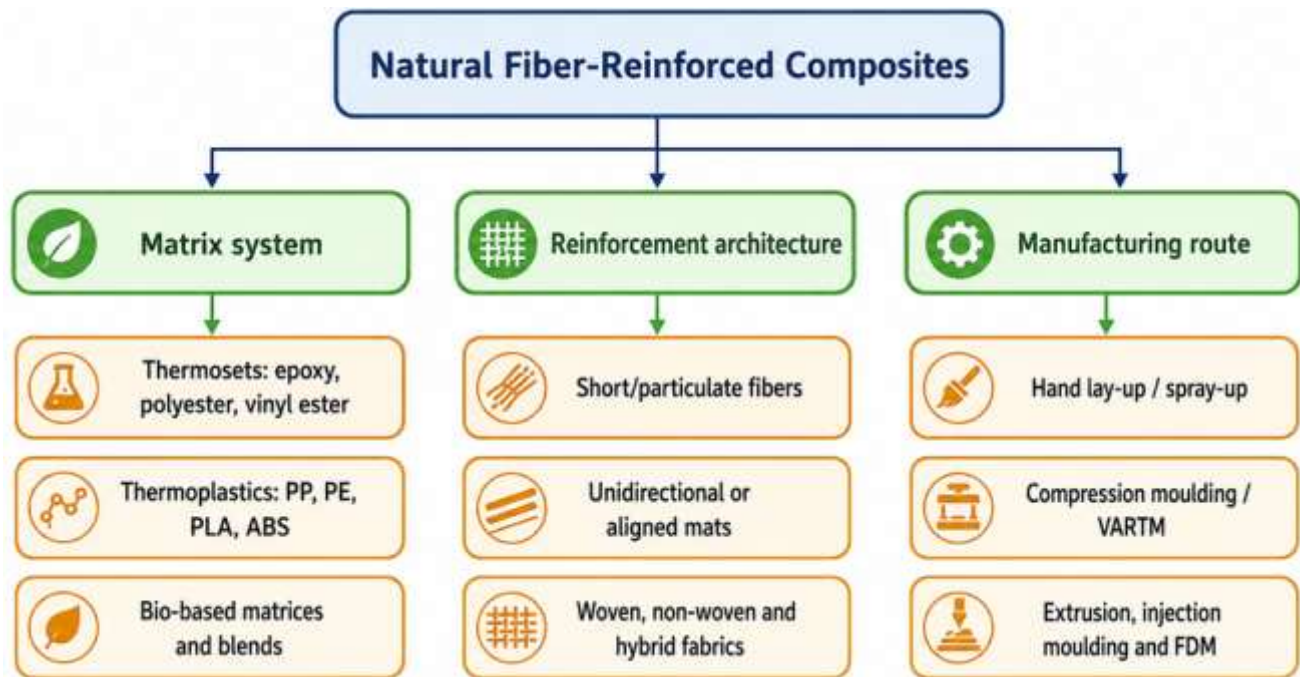


Fig. 2. Taxonomy of material systems, reinforcement architectures and fabrication routes considered.

Bio-based matrices further improve sustainability but often require better interface control. Reinforcement configurations range from short or particulate fibers to unidirectional mats, woven fabrics, non-woven structures, and hybrid architectures, each producing different tensile, flexural, impact, and durability responses. Fabrication methods such as hand lay-up, compression moulding, vacuum-assisted resin transfer moulding, extrusion, injection moulding, and fused deposition modelling strongly affect fiber distribution, resin impregnation, void content, and interfacial adhesion. Therefore, the reviewed studies are compared according to material selection, fiber configuration, processing conditions, performance indicators, limitations, and application suitability.

3.1 Matrix Materials and Constituent Selection

Thermoset matrices dominate laboratory NFRC research because liquid epoxy and polyester can wet woven or aligned fabrics without high melt-processing temperatures. Epoxy usually offers stronger adhesion, lower cure shrinkage and higher strength than unsaturated polyester, but it is more expensive and less readily recyclable. Atmakuri et al. compared hemp–flax, banana–pineapple and single-fiber epoxy laminates at a total reinforcement content of 40 wt%; the 25 wt% hemp/15 wt% flax hybrid reached 87.57 MPa flexural strength, while pure banana reinforcement produced 39.36 MPa [3]. Their later epoxy–ecopoly comparison confirmed that matrix substitution changes flexural and interlaminar performance even when fiber architecture is maintained: petroleum-derived epoxy showed higher strength, whereas bio-based ecopoly improved renewable content but exhibited weaker interfacial transfer [14]. Kumar et al. showed that chemically treated sugarcane-bagasse fibers can reinforce epoxy–polyester systems, although fiber length and variety materially affected density, strength and abrasive wear [6]. These findings indicate that matrix selection must account for viscosity, curing, polarity, cost and end-of-life strategy rather than tensile properties alone.

Thermoplastic matrices offer faster processing and potential remelting, but their higher viscosity makes impregnation of natural-fiber bundles more difficult. Sunny and Pickering overcame this limitation by controlling polypropylene sheet

thickness and stacking distance, enabling approximately 60 wt% aligned hemp with 44.8 MPa tensile strength, 6.2 GPa tensile modulus, 97.6 MPa flexural strength and 18 kJ/m² impact strength [7]. Sayeed et al. compared 30–40 wt% jute, kenaf and pineapple-leaf-fiber polypropylene; reinforced specimens exhibited tensile strengths of approximately 43–58 MPa, flexural strengths of 53–67 MPa and impact strengths of 25–46 kJ/m², with pineapple leaf fiber giving the best overall balance and jute providing high stiffness [15]. Seculi et al. found comparable stiffness development in abaca-reinforced bio-polyethylene and conventional HDPE when fiber content and process conditions were controlled [16]. The remaining gap is the limited number of studies that compare a bio-based and conventional matrix using the same fiber lot, architecture, moisture state and processing history.

Biodegradable PLA systems and hybrid matrices are developing rapidly. Jamadi et al. demonstrated that chemically treated kenaf can be compounded into PLA filament for fused deposition modelling, but the reinforcement benefit depends on treatment, thermal stability, filament diameter and printing settings [13]. Sriseubsai and Praemettha optimized PLA/sisal/coir blends using mixture design; PLA–sisal achieved approximately 58.09 MPa tensile strength, while PLA–coir reached 36.71 kJ/m² impact resistance, and the optimum hybrid contained 95.22% PLA, 0.78% sisal and 4.00% coir [17]. Such results show that one fiber can supply stiffness while another contributes toughness, yet low optimum fiber loading also reveals the severe rheological and adhesion constraints of biodegradable thermoplastics. Future matrix research should report melt flow, crystallinity, matrix–fiber contact angle, recyclability and ageing alongside strength.

Mineral and cementitious matrices create a distinct interface problem because the highly alkaline pore solution can degrade lignocellulosic constituents even though natural fibers arrest shrinkage cracks and improve post-cracking integrity. Pons Ribera et al. evaluated hemp, flax, miscanthus and bamboo dosages from 0.4 to 4 kg/m³ in screed and observed that rigid fibers generally supported flexural response but reduced workability as dosage and water demand increased [18]. This evidence expands the review beyond polymers and shows that the optimum fiber is matrix-dependent: a rough hydrophilic surface may aid mechanical anchorage in cement while the same chemistry increases water sensitivity in a non-polar polymer. Comparative research should therefore separate interface mechanisms for thermoset, thermoplastic and mineral matrices.

Matrix modification with nanoclay, elastomers, bio-resins or recycled polymers provides another design axis. Chee et al. reported approximately 55.82 MPa tensile and 105 MPa flexural strength for an optimized bamboo/kenaf–nanoclay epoxy system, while excessive nanoclay promoted agglomeration and local stress concentration [5]. Nanofillers can increase matrix modulus, reduce crack growth and modify thermal response, but they may also increase viscosity and obstruct fiber wetting. A credible comparison must therefore distinguish direct nanoscale reinforcement from indirect process penalties. The optimum filler level should be justified through dispersion evidence, rheology and fracture morphology rather than strength alone.

Table 1. Representative Material–Fiber–Fabrication Systems and Reported Results

Author, year	Material system	Fabrication	Key inputs	Reported results	Main limitation
Atmakuri et al., 2020 [3]	Hemp/flax and banana/PALF–epoxy	Hand lay-up	40 wt% total fiber; hybrid ratios	25H/15F flexural strength 87.57 MPa; ILSS pure hemp 13.01 MPa Treated flax storage modulus 5.0 GPa at 25°C; 60-day loss ~8% vs ~49% untreated	Void fraction and process repeatability not fully controlled
Fiore et al., 2020 [4]	Flax, jute and flax/jute–epoxy	Laminate processing; salt-fog ageing	NaHCO ₃ treatment; 30/60 days	Optimum system ~55.82 MPa tensile and ~105 MPa flexural strength	Treatment response differed between flax and jute
Chee et al., 2021 [5]	Bamboo/kenaf–nanoclay–epoxy	Hybrid laminate processing	Fiber hybridisation; nanoclay loading	Treated, shorter and uniformly dispersed	Nanoclay agglomeration at excessive loading
Kumar et al., 2021 [6]	Bagasse leaf fiber–epoxy/polyester	Mixing and moulding	Fiber variety, alkali treatment and length		Ageing and long-term moisture not

Author, year	Material system	Fabrication	Key inputs	Reported results	Main limitation
Jamadi et al., 2021 [13]	Chemically treated kenaf–PLA	Compounding, filament extrusion and FDM	Treatment and printing parameters	fibers improved strength and wear Treatment improved mechanical and thermal behaviour	comprehensively assessed Rheology and interlayer bonding constrained performance
Han et al., 2022 [8]	Kenaf–ABS	Twin-screw extrusion + FDM	0–10 vol% kenaf	Tensile 23.20 MPa neat ABS; 11.48 MPa at 5%; 18.59 MPa at 10%	Porosity and weak interfacial bonding
Sunny and Pickering, 2022 [7]	Aligned hemp–PP	Compression moulding	Up to ~60 wt% hemp	Tensile 44.8 MPa; modulus 6.2 GPa; flexural 97.6 MPa	Porosity increased at high fiber content
Atmakuri et al., 2022 [14]	Hemp/flax with epoxy or ecopoxy	Hand lay-up + FEA comparison	Matrix type and hybrid ratio	25H/15F best flexural response; epoxy exceeded ecopoxy	Limited loading modes and idealised interface
Pisupati and Deléglise-Lagardère, 2022 [9]	Flax + waste glass–epoxy	Vacuum infusion/autoclave	5–20% waste glass core	20% addition: flexural +47%; impact +114%	Vacuum infusion gave poor consolidation
Altaee and Mostafa, 2023 [10]	Jute–glass/epoxy interply and intraply	Five-ply laminate fabrication	Five stacking/yarn arrangements	2GJ2G highest flexural; G1J1 tensile ~41% above G1J2	Strong dependence on stacking sequence
Sayeed et al., 2023 [15]	Jute/kenaf/PALF–PP	Thermoplastic compounding	30, 35 and 40 wt%	Tensile 43–58 MPa; flexural 53–67 MPa; impact 25–46 kJ/m ²	Interfacial gaps remained
Venkatesh et al., 2023 [19]	Layered natural fiber–epoxy hybrid	Layered laminate fabrication	Fiber layer sequence	Tensile 57.9 ± 1.2 MPa; flexural 78.65 ± 1.8 MPa	Ageing and repeatability not established
Seculi et al., 2023 [16]	Abaca–bio-PE and abaca–HDPE	Thermoplastic compounding/ moulding	Matrix type and fiber content	Bio-PE stiffness comparable with HDPE	Impact, water absorption and recycling limited
Pons Ribera et al., 2023 [18]	Hemp/flax/miscanthus/bamboo–screed	Mortar mixing and casting	0.4–4 kg/m ³ dosage	Rigid fibers supported flexural response but reduced workability	Alkaline durability requires study
Rachtanapunn et al., 2024 [11]	Bamboo–epoxy	Argon plasma + moulding	Plasma duration	Tensile strength increased ~37 to ~45 MPa at 30 min	Scale-up and energy cost not evaluated
Rachtanapunn et al., 2024 [12]	Bamboo/hemp–epoxy	Comparative plasma treatments	Gas, duration and fiber species	Treatment effects varied by fiber; untreated bamboo flexural ~55.9 MPa	Excessive treatment may damage fibers
Tasgin et al., 2024 [20]	Cotton/sisal/coir/wool–epoxy	VARTM	Fiber species under common process	Different mechanical, wear and thermal rankings	Long-term ageing limited
Seyoum et al., 2024 [21]	Grewia ferruginea–polyester	Short-fiber moulding	10–30 mm; multiple wt%	Optimum 25 wt%, 10 mm: tensile 18.3 MPa; flexural 35.2 MPa	Durability and impact not reported

Author, year	Material system	Fabrication	Key inputs	Reported results	Main limitation
Hamzat et al., 2025 [22]	Heterogeneous fiber-composite data	Five ML regressors	Literature + in-house variables	ETR: R^2 0.94 heterogeneous; 0.99 in-house	Heterogeneity increased MAE/RMSE
Sriseubsai and Praemettha, 2025 [17]	PLA–sisal–coir	Internal mixing + compression moulding	Constrained mixture proportions	PLA–sisal tensile 58.09 MPa; PLA–coir impact 36.71 kJ/m ²	Optimum total fiber only 4.78%
Gebremichael et al., 2025 [23]	Woven sisal–polyester	Hand lay-up + manual compression	25–40 wt%; stacking sequence	40 wt%, 90/0/45: tensile 68.409 MPa; flexural 64.276 MPa	Component validation absent
Soundararajan et al., 2026 [24]	Alkali-treated flax/kenaf–epoxy	Compression moulding	20 wt% kenaf; 0–20 wt% flax	20/20 hybrid: tensile ~107.8 MPa; flexural ~197.7 MPa	Moisture, fatigue and repeatability require validation

Table 1 demonstrates that high reported strength is associated with different mechanisms in different systems: aligned high-fiber-content thermoplastics depend on impregnation distance, woven hybrids depend on ply positioning, and short-fiber systems depend on dispersion and critical length. Values should therefore be compared within their material and process context rather than treated as a universal ranking.

3.2 Fiber Type, Architecture, Loading, and Surface Modification

Fiber species influences composite behaviour through cellulose crystallinity, microfibril angle, lumen structure, aspect ratio, lignin content and surface chemistry. High-cellulose fibers such as flax, hemp, jute, kenaf and bamboo generally contribute high modulus, while coir and wool can improve energy absorption or insulation. Tasgin et al. compared cotton, sisal, coir and wool in epoxy using vacuum-assisted resin transfer moulding and found substantial differences in tensile, flexural, wear and thermal response, demonstrating that mechanical ranking cannot be transferred directly to tribological or thermal applications [20]. Sayeed et al. similarly reported that pineapple-leaf-fiber/PP produced the strongest overall mechanical balance, whereas jute-containing composites showed comparatively high stiffness [15]. The intrinsic fiber property is only a starting point; lumen collapse, fiber damage during extraction, moisture and interfacial wetting determine how much of that property is realized in a composite.

Architecture and orientation control load transfer. Random short fibers are easier to mix and mould but require a sufficient critical length and often develop anisotropic orientation during flow. Aligned mats and unidirectional plies maximize strength along the reinforcement axis, while woven or multidirectional laminates sacrifice peak uniaxial strength for more balanced in-plane response. Altaee and Mostafa showed that jute–glass interply sequence strongly affected tensile, flexural and impact behaviour; the 2GJ2G sequence provided the highest flexural performance, while the GJGJG configuration delivered the best combined specific properties [10]. Gebremichael et al. reported that a 90°/0°/45° woven sisal arrangement outperformed random and non-woven variants at 40 wt% [23]. Venkatesh et al. obtained 57.9 ± 1.2 MPa tensile strength and 78.65 ± 1.8 MPa flexural strength by optimizing layered natural-fiber/epoxy architecture [19]. These studies support architecture-specific design instead of treating fiber percentage as an isolated variable.

Surface modification is intended to remove weak surface constituents and improve chemical or mechanical coupling. Fiore et al. showed that sodium bicarbonate treatment increased the initial storage modulus of flax/epoxy from about 3.4 to 5.0 GPa and limited the 60-day salt-fog modulus reduction to about 8%, compared with approximately 49% for untreated flax; however, the initial modulus of jute laminates decreased after the same treatment [4]. Rachtanapun et al. increased bamboo/epoxy tensile strength from roughly 37 to 45 MPa after 30 min argon-plasma treatment [11], while their comparative plasma study showed that gas type, exposure duration and fiber species generate distinct surface and flexural responses [12]. The research gap is the absence of standardized treatment severity indices that relate concentration, temperature, time and energy to cellulose damage, surface energy and long-term moisture resistance.

Fiber length and loading exhibit an optimum rather than a monotonic relationship. Below the critical embedded length, stress cannot be transferred sufficiently before the fiber debonds; above the processing limit, long fibers entangle, resist flow and trap air. The *Grewia ferruginea* study identified 10 mm and 25 wt% as the best tested combination, while longer

fibers and higher contents reduced uniformity [21]. The aligned hemp/PP study reached much higher loading because the architecture minimized random entanglement and reduced polymer travel distance [7]. These results show that an optimum percentage is not transferable between short-random and aligned continuous systems. Authors should report both wt% and calculated vol%, fiber-length distributions after processing and the orientation tensor when flow-induced alignment is expected.

Hybridisation can be designed at several scales: two natural fibers may be blended to balance stiffness and toughness, glass or basalt plies may protect a natural-fiber core, and particles or nanofillers may modify the matrix between fibers. The benefits are strongly sequence-dependent. Placing stiff synthetic plies near outer bending surfaces can raise flexural capacity, whereas natural-fiber-rich inner layers reduce density and improve damping. Nevertheless, hybrid systems complicate recycling and can create multiple interfaces with different thermal expansion and moisture response. Future studies should quantify the hybrid effect relative to rule-of-mixtures predictions and report whether the improvement is synergistic or merely reflects a higher proportion of the stronger constituent.

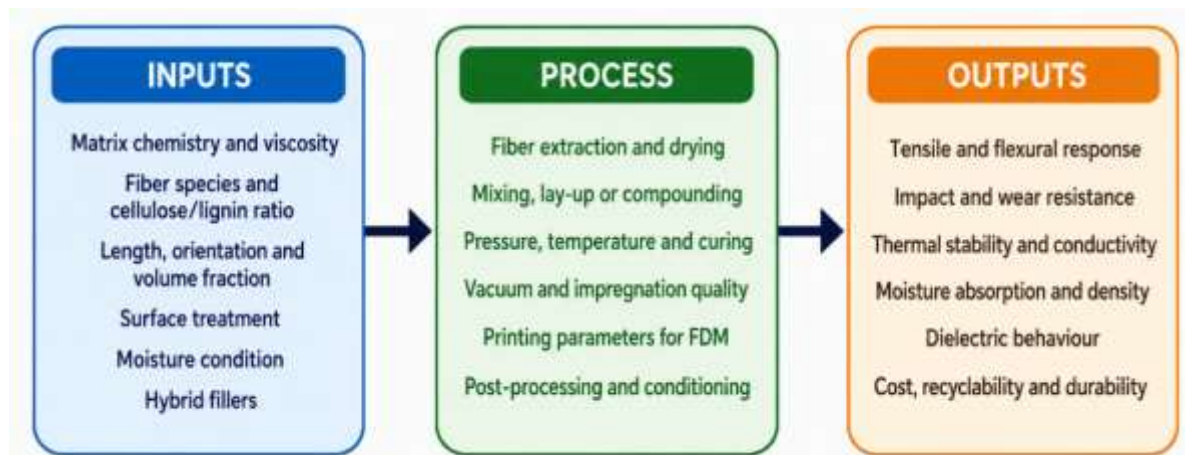


Fig. 3. Integrated input–process–output framework for natural fiber composite performance.

3.3 Fabrication Routes, Process Quality, and Additive Manufacturing

Hand lay-up remains common because it requires inexpensive tooling and accommodates woven fabrics and complex, low-volume shapes. Its disadvantages are manual resin distribution, variable fiber fraction, resin-rich regions, air entrapment and operator-dependent compaction. Atmakuri et al. used hand lay-up successfully for comparative hybrid laminates, but the method limits precise attribution of small property differences to material composition [3]. Manual compression after lay-up, as used in the sisal/polyester study by Gebremichael et al., improves thickness and wetting but still provides less process control than closed-mould methods [23]. Compression moulding is particularly effective for aligned mats and thermoplastic sheets; Sunny and Pickering demonstrated that reducing the polymer-flow distance enabled high hemp content without complete loss of wetting [7]. The consistent trend is that applied pressure improves consolidation only when the matrix remains sufficiently mobile and air has an escape path.

Vacuum-assisted processing provides lower void content and more uniform resin distribution for fabric laminates. Fiore et al. used controlled laminate manufacture before environmental ageing [4], and Tasgin et al. applied VARTM to compare four fiber types under a common epoxy process [20]. However, vacuum pressure alone cannot overcome a low-permeability preform. Pisupati and Deléglise-Lagardère found that bundled, randomly arranged waste glass in a flax preform obstructed resin flow during vacuum infusion; autoclave processing achieved more reliable consolidation, while void content in vacuum-infused material increased from about 2.8% to 5.2% after 10% waste-glass addition [9]. Process selection must therefore be linked to preform permeability, resin viscosity, fiber compressibility and target thickness.

Thermoplastic compounding and additive manufacturing introduce different defects. Twin-screw extrusion distributes short fibers but can shorten them and orient them along flow. FDM adds raster angle, layer height, nozzle temperature, infill and interlayer diffusion as controlling variables. Jamadi et al. showed that chemical treatment and thermal compatibility are prerequisites for kenaf/PLA filament [13]. Han et al. reported non-monotonic tensile and flexural response with kenaf/ABS loading because porosity and poor fiber–matrix adhesion offset reinforcement [8]. Additive manufacturing is therefore attractive for geometry and material efficiency, but its current performance is governed by filament quality and layer bonding rather than the nominal fiber strength. Future work should report filament diameter

tolerance, fiber-length distribution before and after extrusion, rheology, crystallinity, raster orientation and void morphology.

Pre-processing and cure control are important across all routes. Natural fibers must be dried sufficiently to prevent vapor formation and hydrolytic degradation, but excessive drying can embrittle fibers or alter surface chemistry. In thermosets, resin–hardener ratio, exotherm, post-cure and storage temperature influence crosslink density; in thermoplastics, residence time and melt temperature can degrade hemicellulose before the polymer is fully processed. A robust fabrication study should therefore include incoming moisture, cure or thermal history, achieved fiber fraction, density, void content and dimensional variability. Without these data, apparent material improvements may reflect a better batch rather than a reproducible process.

Industrial scale-up further requires process-capability information. Laboratory coupons are often produced one panel at a time, whereas commercial manufacture must maintain fiber distribution, moisture, cure and dimensions over many cycles. Statistical measures such as coefficient of variation, process capability indices and reject rates are rarely reported. Tool wear, fiber dust, odor, emissions, maintenance and worker handling also influence technology selection. A route that gives the highest laboratory strength may be unsuitable if its cycle time, energy use or variability is excessive.

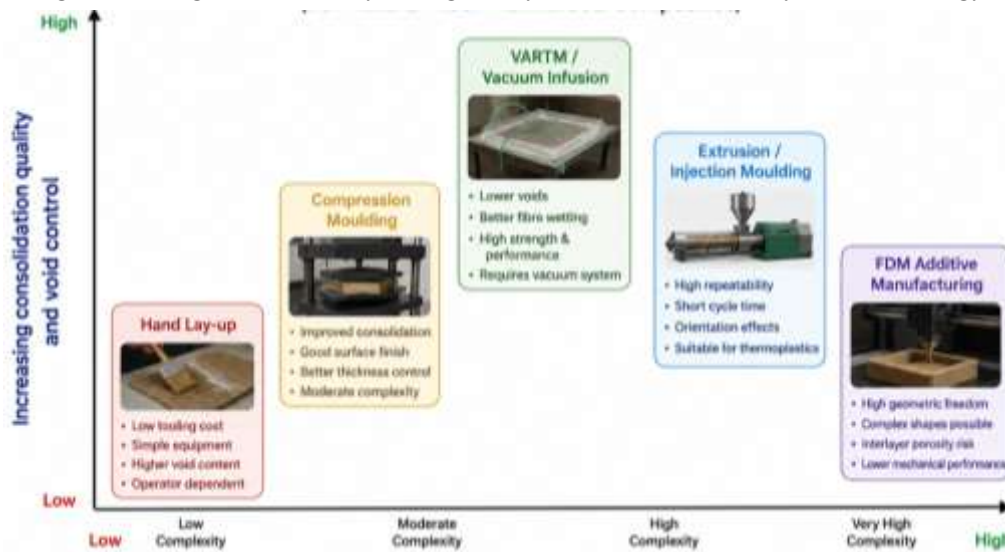


Fig. 4. Qualitative relationship between fabrication route, consolidation control and geometric flexibility.

The fabrication route–quality map compares major manufacturing methods for natural fiber-reinforced composites according to consolidation quality, void control, geometric flexibility, and process complexity. Hand lay-up offers low tooling cost but produces higher void content and operator-dependent quality. Compression moulding improves thickness control and consolidation, while VARTM provides superior fiber wetting and lower porosity. Extrusion and injection moulding support repeatable thermoplastic production. FDM enables highly complex geometries; however, interlayer porosity and comparatively lower mechanical performance remain important limitations.

Table 2. Fabrication Methods, Quality Drivers and Application Suitability

Method	Suitable reinforcement	Main control variables	Typical advantage	Frequent defect	Best-fit application
Hand lay-up	Woven mats, fabrics, hybrid plies	Resin ratio, rolling, cure time, operator skill	Lowest tooling cost and flexible geometry	Air pockets, resin-rich zones, variable thickness	Prototypes, panels and low-volume parts
Compression moulding	Short fibers, aligned mats, thermoplastic sheets	Temperature, pressure, dwell, flow distance	High consolidation and repeatable thickness	Fiber movement or incomplete wetting at excessive loading	Automotive interiors, boards, medium-volume parts

VARTM / vacuum infusion	Woven and non-woven preforms	Permeability, vacuum level, viscosity, inlet/vent design	Low voids and good surface finish	Dry spots in low-permeability preforms	Large lightweight laminates
Autoclave	Fabric laminates and hybrid cores	Vacuum, external pressure, cure cycle	Highest consolidation among reviewed routes	High energy and equipment cost	High-quality structural laminates
Extrusion / injection	Short fibers and particulate fillers	Screw design, temperature, residence time, moisture	High throughput and repeatability	Fiber shortening and flow-induced orientation	Consumer goods and automotive components
FDM	Short-fiber thermoplastic filament	Nozzle temperature, raster, infill, layer height, filament quality	Complex geometry and low material waste	Interlayer voids, nozzle blockage, anisotropy	Customized low-load parts and prototypes

The fabrication comparison indicates that no route is universally superior. Closed-mould and vacuum methods improve consolidation, whereas extrusion and FDM improve production or geometry. The appropriate selection depends on reinforcement form, matrix rheology, production volume, acceptable anisotropy and economic constraints.

3.4 Computational Modelling, Optimization, and Machine Learning

Analytical and finite-element models reduce the experimental burden by relating constituent properties, orientation and architecture to composite response. Atmakuri et al. combined flexural experiments with Halpin–Tsai-based estimates and finite-element analysis to compare epoxy and ecopoly matrices, obtaining similar trends between numerical and experimental results [14]. Such models are useful for sensitivity studies, but natural fibers violate several simplifying assumptions because diameter, modulus, cross-section and interface strength vary along the fiber. A reliable finite-element model therefore requires experimentally measured orthotropic properties, realistic fiber volume fraction, interface or cohesive parameters, and validation under the same moisture and temperature conditions as the test. Models that assume perfect bonding may overpredict stiffness and suppress pull-out failure.

Data-driven methods are emerging for property prediction and process optimization. Hamzat et al. trained light-gradient boosting, extra trees, decision tree, histogram-gradient boosting and AdaBoost regressors on in-house and literature-derived fiber-composite data. The extra-trees model achieved $R^2 = 0.94$, $MAE = 31.97$ and $RMSE = 47.64$ on the heterogeneous dataset; performance increased to $R^2 = 0.99$, $MAE = 9.53$ and $RMSE = 13.15$ for the more internally consistent in-house data [22]. This difference quantifies the penalty caused by heterogeneous specimen standards and incomplete reporting. Saravanakumar et al. applied ANN and LSTM models to abrasive-water-jet machining of banana-fiber composites, predicting surface roughness, material-removal rate and kerf angle using tuned network configurations [25]. These approaches can reduce testing and machining trials, but generalizability depends on sample size, data distribution and leakage-free validation.

The most promising direction is physics-informed and explainable modelling. Sadik et al. integrated experiments, finite-element analysis and four supervised models—random forest, XGBoost, gradient boosting and k-nearest neighbour—to predict and interpret banana-fiber hybrid-composite behaviour [26]. Explainability tools can identify whether fiber percentage, treatment, matrix fraction, orientation or processing variables dominate a prediction, which is essential when the dataset combines multiple studies. However, ML models trained on literature values can inherit publication bias and hidden inconsistencies in standards, units, conditioning and failure definitions. Future databases should include raw stress–strain data, uncertainty, process settings, fiber chemical composition, microscopy descriptors and negative results. Cross-study validation, external test sets and uncertainty intervals are more important than a single high R^2 value.

Design of experiments and response-surface methods occupy an intermediate position between physics-based and purely data-driven modelling. They are effective when the number of controllable variables is moderate and experiments can be planned to estimate interactions, as illustrated by mixture optimisation of PLA–sisal–coir proportions [17]. Their limitation is local validity: a response surface calibrated within one fiber lot and processing window may not extrapolate

to another matrix, moisture condition or architecture. Combining planned experiments with Bayesian optimisation or active learning could select the next most informative composition, reduce testing and provide uncertainty bounds.

Data architecture is a practical barrier to advanced modelling. Published tables often omit matrix grade, fiber density, exact treatment concentration, specimen conditioning or failed formulations. Ontologies for natural-fiber composites should define common fields and units for constituent chemistry, architecture, processing and test outcomes. Image-derived descriptors from SEM or micro-computed tomography could quantify pull-out length, void size and fiber orientation, allowing multimodal models to connect microstructure with strength. Such databases would also make negative results visible and reduce publication bias toward successful formulations.

Table 3. Computational, Optimisation and Data-Driven Approaches

Study	Approach	Inputs/data	Outputs	Reported performance	Limitation
Atmakuri et al., 2022 [14]	Halpin–Tsai + FEA + experiments	Fiber ratios, epoxy/ecopoxy properties	Flexural response and matrix effect	Numerical and experimental trends were consistent	Idealized interface and limited loading modes
Saravanakumar et al., 2024 [25]	ANN and LSTM	AWJM process variables for banana composite	Ra, MRR and kerf angle	Optimized ANN/LSTM architectures reported	Application-specific machining dataset
Hamzat et al., 2025 [22]	Five ensemble/tree regressors	In-house + literature composite data	Flexural strength	Heterogeneous data: R^2 0.94, MAE 31.97, RMSE 47.64; in-house: R^2 0.99	Dataset heterogeneity and scale dependence
Sadik et al., 2025 [26]	Experiments + FEA + explainable ML	Literature and experimental banana-hybrid data	Mechanical-property prediction and interpretation	Random forest, XGBoost, gradient boosting and kNN compared	External validation remains limited
Sriseubsai and Praemettha, 2025 [17]	Constrained mixture design + t-test	PLA, sisal and coir proportions	Tensile and impact optimization	Optimum: 95.22% PLA, 0.78% sisal, 4.00% coir	Optimum at low total fiber loading

Table 3 shows that model accuracy is highest when data are internally consistent, whereas heterogeneous literature datasets reduce predictive precision. The key research need is not only more algorithms, but standardized, machine-readable datasets and validation protocols that preserve physical interpretability.

3.5 Comparative Performance, Applications, Durability, and Emerging Gaps

Mechanical results across the reviewed studies span a wide range because constituent properties and test configurations differ. Seyoum et al. obtained 18.3 MPa tensile and 35.2 MPa flexural strength for 25 wt% *Grewia ferruginea*/polyester with 10 mm fibers [21]. Gebremichael et al. achieved 68.409 MPa tensile and 64.276 MPa flexural strength from a woven, multidirectional sisal/polyester laminate [23]. Soundararjan et al. reported approximately 107.8 MPa tensile and 197.7 MPa flexural strength for an alkali-treated 20 wt% flax/20 wt% kenaf epoxy composite produced by compression moulding [24]. These differences reflect architecture and consolidation as much as fiber species. Howlader et al. further showed that epoxy and polyester hybrid systems exhibit distinct mechanical and morphological failure modes, highlighting the need to connect strength with fracture-surface evidence [27]. Cross-study interpretation should also identify whether tensile, flexural and impact tests followed recognized procedures such as ASTM D638, ASTM D790 and ASTM D256, respectively [28]–[30].

Durability evidence is less mature than short-term strength data. Fiore et al. demonstrated that environmental ageing can cause a large reduction in dynamic stiffness when treatment and interface quality are inadequate [4]. Water absorption is driven by fiber hydroxyl groups, lumens, voids and interfacial capillaries; cyclic swelling can progressively damage the matrix. Thermal behaviour is controlled by the earlier degradation of hemicellulose and cellulose, matrix glass transition and the formation of char. Tasgin et al. found that cotton, sisal, coir and wool composites gave different wear

and thermal characteristics, making application-specific selection necessary [20]. Many papers nevertheless test dry, unaged coupons and do not evaluate fatigue, creep, ultraviolet exposure, fire, biodegradation or repeated recycling.

Applications reported or proposed include automotive interior and exterior panels, construction screeds and boards, furniture, packaging, consumer goods, acoustic components and customized FDM products. Pons Ribera et al. used 0.4–4 kg/m³ hemp, flax, miscanthus and bamboo in cementitious screed, demonstrating that fiber rigidity and dosage influence workability, shrinkage and flexural response [18]. Pisupati and Deléglise-Lagardère demonstrated a circular-economy route by incorporating waste glass into flax laminates [9]. The central gap is the absence of a common decision framework that combines mechanical performance, durability, density, cost, process energy, renewable content, repairability and end-of-life. Industrial adoption requires component-scale tests and life-cycle data rather than coupon strength alone.

Functional properties are also underrepresented. Natural fibers are generally electrically insulating, but dielectric constant and loss vary with moisture and frequency; thermal conductivity can make one system suitable for insulation and another for heat dissipation. Wear resistance depends on fiber hardness, orientation, matrix removal and the formation of a protective transfer film. Tasgin et al. demonstrated that the composite with the highest mechanical response was not necessarily the best in every wear or thermal condition [20]. Future application screening should use a multi-criteria matrix that includes tensile and flexural performance, impact, wear, thermal conductivity, fire response, dielectric behaviour, water uptake and acoustic damping.

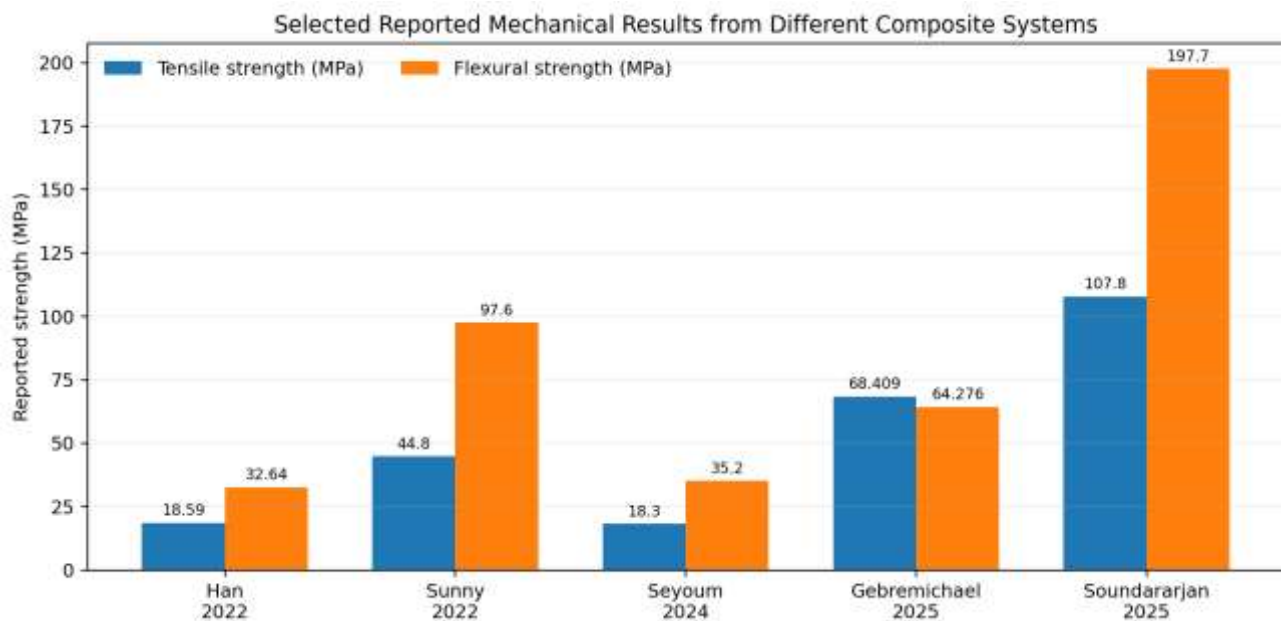


Fig. 5. Selected tensile and flexural strength values reported for different NFRC systems [8], [7], [21], [23], [24].

Component qualification must reproduce service conditions. Automotive panels experience vibration, humidity, temperature cycling and local fastener loads; construction boards require fire, fungal, wet–dry and creep resistance; packaging requires migration, barrier and end-of-life assessment; and furniture components require screw withdrawal, surface durability and dimensional stability. Most reviewed papers stop at coupon-scale tensile or flexural tests. Translating NFRCs to products therefore requires design allowables, joining and repair studies, accelerated ageing models, flammability control and manufacturing quality assurance.

Table 4. Research Limitations and Identified Gaps

Observed limitation	Evidence in literature	Effect on interpretation	Priority research response
Fiber variability	Different source, maturity, extraction and moisture conditions	Large scatter and poor reproducibility	Report chemical composition, density, diameter distribution and conditioning
Interface incompatibility	Hydrophilic fiber with hydrophobic polymer	Pull-out, swelling and loss of strength	Fiber-specific treatment optimization and interface characterization

Observed limitation	Evidence in literature	Effect on interpretation	Priority research response
Process defects	Voids, dry spots, resin-rich zones and interlayer porosity	Measured properties reflect defects rather than intrinsic material	Quantify void fraction, permeability, rheology and process repeatability
Inconsistent testing	Different standards, specimen sizes and loading rates	Weak cross-study comparability	Adopt common ASTM/ISO protocols and share raw stress–strain data
Limited durability	Few long-term ageing, fatigue, creep and UV studies	Uncertain service life	Multi-environment ageing and residual-property models
Small ML datasets	Heterogeneous literature values and incomplete metadata	Overfitting and uncertain extrapolation	Open standardized databases, external validation and uncertainty reporting
Incomplete sustainability evidence	Strength reported without cost, energy or end-of-life	Unclear industrial advantage	Couple mechanics with techno-economic and life-cycle assessment

The gap analysis emphasizes that better experimental reporting is itself a research requirement. Without consistent information on fiber state, void content, specimen conditioning and process parameters, sophisticated modelling cannot distinguish true material effects from laboratory-specific variation.

4. Discussion

The evidence indicates that NFRC performance is controlled by a hierarchy of coupled factors. At the first level, the matrix must wet the fiber and retain adequate stiffness, toughness and environmental resistance. At the second level, the fiber must have sufficient aspect ratio, orientation and integrity to transfer load. At the third level, fabrication must consolidate the preform without creating voids, fiber damage or excessive residual stress. This hierarchy explains why high-strength fibers may underperform in poorly processed systems. The kenaf/ABS FDM results show that fiber addition can decrease tensile strength when interfacial adhesion and porosity dominate [8], while the aligned hemp/PP study demonstrates that high fiber content becomes beneficial when flow distance and consolidation are controlled [7]. Similar contrasts occur in surface treatment: sodium bicarbonate substantially protected flax/epoxy during salt-fog exposure but did not provide the same benefit to jute [4]. Accordingly, the most effective approach is not a universal “best fiber,” but application-specific optimization of the matrix–fiber–process combination.

Fabrication route determines both performance and scalability. Hand lay-up is suitable for low-cost prototypes and low-volume panels but introduces variability that can conceal modest material improvements. Compression moulding offers repeatable thickness and is effective for high-fiber thermoplastic mats and hybrid laminates, provided temperature and pressure allow wetting without excessive fiber movement. VARTM is advantageous for large woven preforms, yet low permeability and bundled fillers can generate dry zones even under vacuum [9]. FDM provides unmatched geometry and material efficiency but currently produces anisotropic parts whose strength depends on filament quality, raster and interlayer fusion [13], [8]. Therefore, process comparison should include void content, fiber-volume fraction, dimensional variation, energy, cycle time and reject rate. Strength alone may favour autoclave or compression processing, whereas production flexibility or recyclability may favour thermoplastic and additive routes.

Computational methods can accelerate this multi-variable optimization, but the reviewed evidence shows a clear dependency on data quality. Hamzat et al. obtained $R^2 = 0.99$ on internally consistent data but $R^2 = 0.94$ with higher errors on heterogeneous literature data [22]. This is still strong predictive performance, yet it demonstrates that algorithm selection cannot compensate fully for inconsistent testing and incomplete metadata. Explainable models integrated with finite-element analysis are promising because they can relate predictions to physically meaningful variables and identify interactions among fiber fraction, orientation, matrix and processing [26]. The next stage of NFRC research should therefore combine standardized experiments, non-destructive defect quantification, multiscale modelling, uncertainty-aware machine learning, component-scale validation and life-cycle assessment. Such integration would allow researchers to identify Pareto-optimal solutions that balance strength, impact resistance, durability, density, cost and environmental benefit rather than maximizing one coupon property.

Application selection should consequently begin with the service environment rather than with the largest reported strength value. For dry interior panels, low density, acoustic damping, moderate impact resistance and economical hand lay-up or compression moulding may be more important than maximum tensile capacity. Automotive trim and semi-structural parts additionally require repeatable impact response, humidity stability, dimensional tolerance, flammability control and scalable cycle time; woven or aligned thermoplastic systems are attractive where recyclability and rapid forming are required, whereas hybrid thermoset laminates remain useful when surface finish and stiffness dominate [7], [10], [23]. Outdoor construction products require moisture barriers, ultraviolet resistance, biological durability and retained properties after wet-dry or salt exposure, making interface treatment and ageing validation essential [4], [11], [12]. Additively manufactured NFRCs offer design freedom and material efficiency, but anisotropy, nozzle wear, fiber shortening and interlayer porosity presently restrict their use in highly loaded components [13], [8]. These contrasts show why cross-study ranking by tensile strength alone is misleading. A defensible material-selection procedure should first define functional constraints, then screen matrix and fiber compatibility, select an architecture and process capable of meeting geometric and production demands, and finally verify performance through standardized mechanical, environmental and component-level tests. Reporting specific properties, retained properties after conditioning, statistical dispersion, void fraction, process energy and end-of-life options would enable more meaningful comparison and support evidence-based transition from laboratory specimens to industrial products.

5. Limitations of the Study

This review is limited by the availability and comparability of published evidence. The formal search emphasized English-language literature from 2020 to June 2026 and publisher-accessible full text; relevant non-English studies, proprietary industrial reports and subscription-only papers may therefore be underrepresented. Database coverage was broad but not equivalent to a direct export from every indexing service. The included studies used different fiber sources, extraction histories, moisture conditioning, matrix grades, specimen geometries, standards, loading rates and environmental conditions. Consequently, reported strength, modulus, wear and thermal values could not be pooled statistically without introducing misleading assumptions. Several papers did not report void fraction, uncertainty, raw data or complete process parameters, and positive-result publication bias may favour successful material combinations. Computational studies also used datasets of different sizes and definitions, limiting direct comparison of accuracy metrics. The conclusions should therefore be interpreted as a structured synthesis of trends and design relationships rather than a universal ranking of natural fibers or manufacturing methods.

- Database limitation: the review depended on accessible scholarly platforms and English full text.
- Methodological heterogeneity: constituent preparation, fabrication and testing procedures varied substantially.
- Data and metric inconsistency: missing uncertainty, void content and raw-data reporting limited quantitative pooling.
- Limited generalisability: coupon-scale laboratory outcomes may not represent industrial components or long-term service.

6. Conclusion

This review systematically evaluated the performance of natural fiber-reinforced composites through the combined effects of matrix material, fiber characteristics, surface modification, architecture, fabrication route and computational support. A PRISMA-guided selection process reduced 650 identified records to 28 primary studies with sufficient methodological and quantitative quality. The reviewed evidence covered epoxy, polyester, polypropylene, polyethylene, PLA, ABS and bio-based matrices; jute, flax, hemp, kenaf, sisal, bamboo, coir, pineapple leaf, banana and less-established plant fibers; and manufacturing routes ranging from hand lay-up and compression moulding to vacuum-assisted processing, extrusion, injection moulding and fused deposition modelling.

The central finding is that no fiber or matrix is universally superior. High performance is achieved when fiber architecture and processing allow efficient load transfer. Aligned hemp/polypropylene reached 44.8 MPa tensile strength and 97.6 MPa flexural strength at high fiber loading, whereas intermediate kenaf loading in printed ABS reduced strength because porosity and weak compatibility offset reinforcement. Hybridization can balance stiffness, toughness and impact resistance, while surface treatments can improve bonding and ageing resistance; however, treatment effects are fiber-specific and excessive chemical or plasma exposure may damage the reinforcement. Closed-mould and vacuum methods generally improve consolidation, but process suitability depends on viscosity, preform permeability, production scale and target geometry.

Finite-element, optimization and machine-learning methods provide valuable tools for navigating the large design space. Ensemble regressors have achieved R^2 values of 0.94 on heterogeneous data and 0.99 on consistent in-house data, confirming both the potential of prediction and the importance of standardized datasets [22]. The principal unresolved issues are fiber variability, moisture sensitivity, inconsistent test methods, incomplete defect reporting, limited fatigue and environmental ageing data, and weak integration of mechanical results with cost and life-cycle performance. Future research should use common conditioning and testing protocols, quantify voids and interface properties, publish machine-readable raw data, apply interpretable and uncertainty-aware models, and validate optimized composites at component scale. The review contributes an integrated material–interface–process framework that can guide application-specific selection and the responsible transition of NFRCs from laboratory coupons to reliable sustainable engineering products.

References

- [1] M. J. Page et al., “The PRISMA 2020 statement: An updated guideline for reporting systematic reviews,” *BMJ*, vol. 372, p. n71, 2021, doi: <https://doi.org/10.1136/bmj.n71>
- [2] S. H. Kamarudin et al., “A review on natural fiber reinforced polymer composites (NFRPC) for sustainable industrial applications,” *Polymers*, vol. 14, no. 17, Art. no. 3698, 2022, doi: <https://doi.org/10.3390/polym14173698>
- [3] A. Atmakuri, A. Palevicius, M. Siddabathula, A. Vilkauskas, and G. Janusas, “Analysis of mechanical and wettability properties of natural fiber-reinforced epoxy hybrid composites,” *Polymers*, vol. 12, no. 12, Art. no. 2827, 2020, doi: <https://doi.org/10.3390/polym12122827>
- [4] V. Fiore, C. Sanfilippo, and L. Calabrese, “Dynamic mechanical behavior analysis of flax/jute fiber-reinforced composites under salt-fog spray environment,” *Polymers*, vol. 12, no. 3, Art. no. 716, 2020, doi: <https://doi.org/10.3390/polym12030716>
- [5] S. S. Chee, M. Jawaid, O. Y. Alothman, and H. Fouad, “Effects of nanoclay on mechanical and dynamic mechanical properties of bamboo/kenaf reinforced epoxy hybrid composites,” *Polymers*, vol. 13, no. 3, Art. no. 395, 2021, doi: <https://doi.org/10.3390/polym13030395>
- [6] S. Kumar, L. Prasad, V. K. Patel, V. Kumar, A. Kumar, A. Yadav, and J. Winczek, “Physical and mechanical properties of natural leaf fiber-reinforced epoxy polyester composites,” *Polymers*, vol. 13, no. 9, Art. no. 1369, 2021, doi: <https://doi.org/10.3390/polym13091369>
- [7] T. Sunny and K. L. Pickering, “Improving polypropylene matrix composites reinforced with aligned hemp fibre mats using high fibre contents,” *Materials*, vol. 15, no. 16, Art. no. 5587, 2022, doi: <https://doi.org/10.3390/ma15165587>
- [8] S. N. M. F. Han, M. M. Taha, M. R. Mansor, et al., “Investigation of tensile and flexural properties of kenaf fiber-reinforced acrylonitrile butadiene styrene composites fabricated by fused deposition modeling,” *J. Eng. Appl. Sci.*, vol. 69, Art. no. 52, 2022, doi: <https://doi.org/10.1186/s44147-022-00109-0>
- [9] A. Pisupati and M. Deléglise-Lagardère, “Mechanical performance of flax fiber composites with waste glass fibers as a core structure,” *Materials*, vol. 15, no. 24, Art. no. 9017, 2022, doi: <https://doi.org/10.3390/ma15249017>
- [10] M. A. Altaee and N. H. Mostafa, “Mechanical properties of interply and intraply hybrid laminates based on jute-glass/epoxy composites,” *J. Eng. Appl. Sci.*, vol. 70, Art. no. 121, 2023, doi: <https://doi.org/10.1186/s44147-023-00293-7>
- [11] P. Rachtanapun et al., “Effect of plasma treatment on bamboo fiber-reinforced epoxy composites,” *Polymers*, vol. 16, no. 7, Art. no. 938, 2024, doi: <https://doi.org/10.3390/polym16070938>
- [12] P. Rachtanapun et al., “Comparison of effects of plasma surface modifications of bamboo and hemp fibers on mechanical properties of fiber-reinforced epoxy composites,” *Polymers*, vol. 16, no. 23, Art. no. 3394, 2024, doi: <https://doi.org/10.3390/polym16233394>
- [13] A. H. Jamadi, N. Razali, M. Petru, M. M. Taha, N. Muhammad, and R. A. Ilyas, “Effect of chemically treated kenaf fibre on mechanical and thermal properties of PLA composites prepared through fused deposition modeling (FDM),” *Polymers*, vol. 13, no. 19, Art. no. 3299, 2021, doi: <https://doi.org/10.3390/polym13193299>
- [14] A. Atmakuri, A. Palevicius, A. Vilkauskas, and G. Janusas, “Numerical and experimental analysis of mechanical properties of natural-fiber-reinforced hybrid polymer composites and the effect on matrix material,” *Polymers*, vol. 14, no. 13, Art. no. 2612, 2022, doi: <https://doi.org/10.3390/polym14132612>

- [15] M. M. A. Sayeed et al., "Assessing mechanical properties of jute, kenaf, and pineapple leaf fiber-reinforced polypropylene composites: Experiment and modelling," *Polymers*, vol. 15, no. 4, Art. no. 830, 2023, doi: <https://doi.org/10.3390/polym15040830>
- [16] F. Seculi, F. X. Espinach, F. Julián, M. Delgado-Aguilar, P. Mutjé, and Q. Tarrés, "Comparative evaluation of the stiffness of abaca-fiber-reinforced bio-polyethylene and high density polyethylene composites," *Polymers*, vol. 15, no. 5, Art. no. 1096, 2023, doi: <https://doi.org/10.3390/polym15051096>
- [17] W. Sriseubsai and A. Praemettha, "Hybrid natural fiber composites of polylactic acid reinforced with sisal and coir fibers," *Polymers*, vol. 17, no. 1, Art. no. 64, 2025, doi: <https://doi.org/10.3390/polym17010064>
- [18] S. Pons Ribera et al., "Valorization of vegetal fibers (hemp, flax, miscanthus and bamboo) in a fiber-reinforced cement-based screed," *Materials*, vol. 16, no. 6, Art. no. 2203, 2023, doi: <https://doi.org/10.3390/ma16062203>
- [19] R. Venkatesh, S. Ballal, A. M. Krishnan, S. Prabakaran, S. Mohankumar, and E. Ramaraj, "Effect of fiber layer formation on mechanical and wear properties of natural fiber filled epoxy hybrid composites," *Heliyon*, vol. 9, Art. no. e15934, 2023, doi: <https://doi.org/10.1016/j.heliyon.2023.e15934>
- [20] Y. Tasgin, G. Demircan, S. Kandemir, and A. Acikgoz, "Mechanical, wear and thermal properties of natural fiber-reinforced epoxy composite: Cotton, sisal, coir and wool fibers," *J. Mater. Sci.*, vol. 59, pp. 10844–10857, 2024, doi: <https://doi.org/10.1007/s10853-024-09810-2>
- [21] D. Seyoum, A. Asratie, R. Gnanadurai, and Y. Gzate, "Experimental characterization of Grewia ferruginea fiber reinforced polyester matrix composite materials," *Funct. Compos. Mater.*, vol. 5, Art. no. 7, 2024, doi: <https://doi.org/10.1186/s42252-024-00057-3>
- [22] A. K. Hamzat et al., "Development of robust machine learning models for predicting flexural strengths of fiber-reinforced polymeric composites," *Hybrid Adv.*, vol. 8, Art. no. 100385, 2025, doi: <https://doi.org/10.1016/j.hybadv.2025.100385>
- [23] G. Gebremichael, S. T. Mekonone, T. M. Baye, and A. A. Ejigu, "Mechanical and microstructural characterization of sisal fiber-reinforced polyester laminate composites for improved durability in automotive applications," *J. Mater. Sci.: Compos.*, vol. 6, no. 1, pp. 1–14, 2025, doi: <https://doi.org/10.1186/s42252-024-00064-4>
- [24] S. Soundararajan et al., "Analyse the mechanical properties of flax-kenaf bio-fiber reinforced hybrid composites," *Discover Mater.*, vol. 6, Art. no. 40, 2026, doi: <https://doi.org/10.1007/s43939-025-00510-5>
- [25] S. Saravanakumar et al., "Enhancing machining accuracy of banana fiber-reinforced composites with ensemble machine learning," *Measurement*, vol. 235, Art. no. 114912, 2024, doi: <https://doi.org/10.1016/j.measurement.2024.114912>
- [26] M. M. H. Sadik et al., "Integrating experiments, finite element analysis, and explainable machine learning for natural fiber based hybrid composites," *Results Mater.*, vol. 29, Art. no. 100835, 2025, doi: <https://doi.org/10.1016/j.rinma.2025.100835>
- [27] M. I. Howlader et al., "Mechanical and morphological analysis of natural fiber-reinforced epoxy and polyester hybrid composites," *Results Eng.*, vol. 26, Art. no. 105010, 2025, doi: <https://doi.org/10.1016/j.rineng.2025.105010>
- [28] ASTM International, "ASTM D638: Standard test method for tensile properties of plastics," West Conshohocken, PA, USA, latest ed.
- [29] ASTM International, "ASTM D790: Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," West Conshohocken, PA, USA, latest ed.
- [30] ASTM International, "ASTM D256: Standard test methods for determining the Izod pendulum impact resistance of plastics," West Conshohocken, PA, USA, latest ed.